Mathematical model of 30CrMnSi alloy steel absorptivity evolution under 1.07μm cw-laser irradiation

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ABSTRACT

In this paper we build an experimental apparatus to measure the reflectivity and temperature of the foil in different conditions. The experimental results show that the growth of oxide film can be divided into 3 stages which corresponding to logarithmic, linear and parabolic rate law. A mathematical model is introduced to explain the phenomena observed in experiment. Numeral calculations are made for 30CrMnSi steel while cw-laser wavelength is 1.07μm. The numerical solutions are in agreement with the experimental data.

Keywords: mathematical model, absorptivity evolution, laser, 30CrMnSi steel

1. INTRODUCTION

An understanding of the fundamental absorption mechanisms plays a vital role in laser heating of metals. The absorptivity, which is the fraction of the incident laser light which is absorbed, depends on a number of different parameters. These include laser parameters such as wavelength, intensity, polarization and angle of incidence and material properties such as composition, temperature, surface roughness, oxide layers and contamination[1-5]. The theoretical and experimental studies of light interaction with metals have usually been concentrated on pure metallic elements with surfaces as smooth and clean as possible. Following the treatment of Prokhorov[5] the absorptivity can be wrote as $A=A_{int}+A_{ext}$, where A_{int} is determined by the intrinsic(bulk) properties of the metal and vary with temperature, A_{ext} is determined by the external(surface) conditions and fixed once be fabricated. This method is useful to predict the absorptivity at room temperature and can calculate the variation of absorptivity with temperature which caused by intrinsic properties of materials.

Experimental data show an absorptivity between 28.6% and 30% for a Nd:YAG laser beam incident on polished low alloy steels. Absorptivity increases about 1% ~ 2% when the surface was heated up to 1400℃[6] in inert atmosphere. This is not always true in laser material processing because of the atmosphere difference. When metals is irradiated in oxidizing atmosphere, a oxide film will growth and cause the absorptivity rise up severely. Some researches have been made on the formation of oxidation layer under pulsed laser irradiation [6, 11-14]. The kinetics of oxide film growth follows parabolic rate law, and the multi-beam interference model of an absorbing film on an absorbing substrate was used to calculate the oxide film depth dependence of absorbtivity. But none of them measured the absorptivity variation in-situ. Thus no direct experimental data can be used to validate the theoretical results.

In this work, our goal is to build an experimental apparatus to measure the temperature and absorptivity in-situ and give information about the mechanism of absorptivity evolution under cw-laser irradiation.

2. EXPERIMENTAL

An experimental apparatus was constructed to measure the reflectivity and temperature of the sample simultaneous in different environment. The schematic diagram of the experiment is shown in Fig.1.

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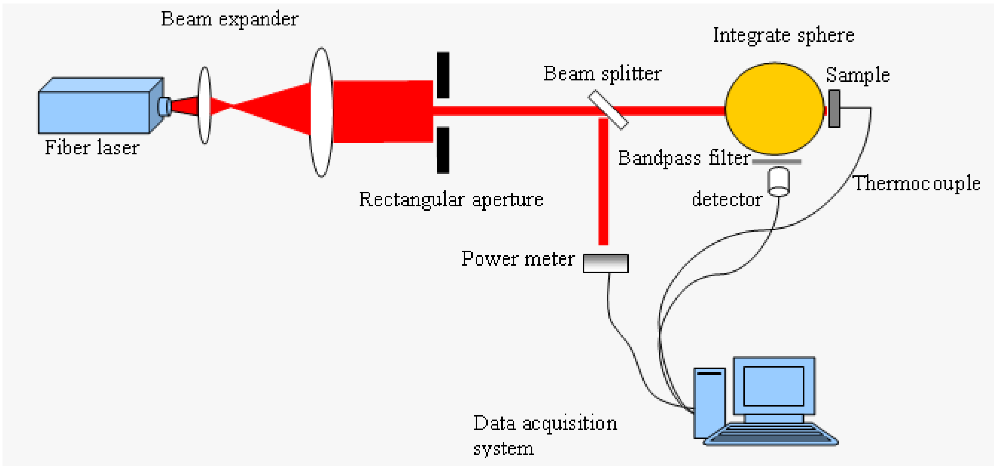


Fig 1. Schematic diagram of the experiment for measuring reflectivity and temperature.

The main features of the installation are presented in Fig 1. Continuous wave fiber laser radiation was horizontally directed through a beam expender, a square graphite aperture sized 4.5mm×4.5mm was used to select the center flat portion of the Beam. With a beam splitter, the main beam was irradiated on a foil dimensions 5mm×5mm×0.5mm and the reference beam was irradiated on a power meter to monitor the flux fluctuation. Substitution method of diffuse reflectance measurement was selected. The integrating sphere was fabricated by Labsphere Inc. A band-pass filter (having transmission peak in the range λ=1.07μm and a transmission bandwidth $\Delta\lambda$=0.01μm) was placed before detector to eliminate the light emission by the heated target itself. The radiation spot covered almost the entire target area. The K type thermocouples (Φ=0.1mm) were welded on the unirradiated side. The foil was supported by thermocouple wires in order to insulate from the environment. The temperature, reflectivity and laser flux fluctuation signals were acquired by a data acquisition system.

The low alloy steel 30CrMnSi was used in the study. The chemical composition of the materials is given in Table 1.

Table 1

Chemical composition of the steels [wt.%]

	C	Mn	Si	Cr	Ni
30CrMnSi	0.30	0.92	1.10	1.02	0.3

The sample was heated up to 1000℃ in inert atmosphere to avoid oxidation and cooled down to room temperature first. Then the same heating cycle was execute in atmosphere. Last the sample with oxide undergoes heating cycle in atmosphere. The temperature dependence of absorptivity under different conditions is shown in Fig 2.

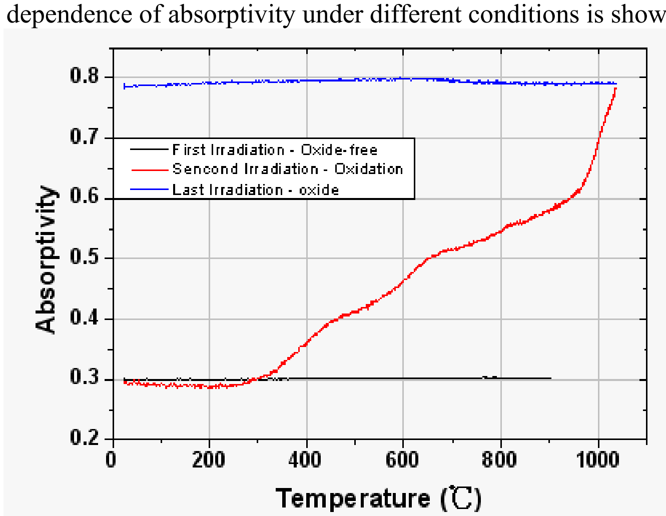
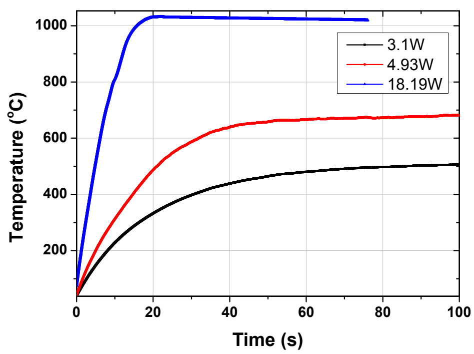


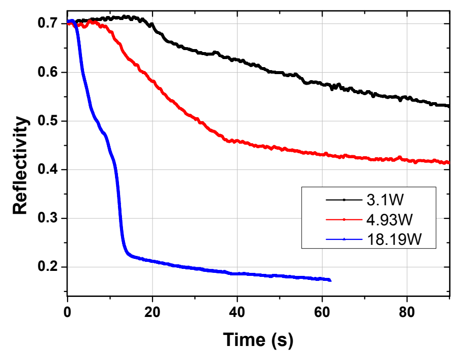
Fig 2. Temperature dependence of absorptivity under different conditions.

From Fig 2, the result shows that the absorptivity of steel is insensitive to temperature at 1.07μm in inert atmosphere, and the oxide layer is the main reason for absorptivity changing under laser irradiation. Oxide layer become opacity with the depth increasing.

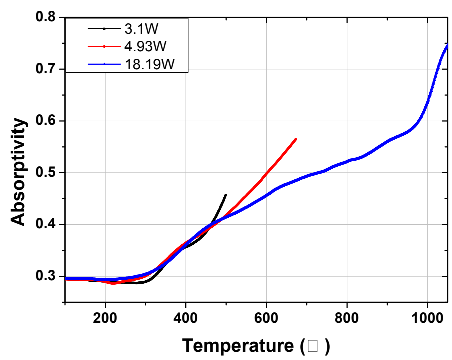
The temperature and absorptivity evolution was recorded at different laser power, the results are shown in Fig 3.



(a) Dependence on time of temperature



(b) Dependence on time of reflectivity



(c) Dependence on temperature of absorptivityr

Fig 3. Experimental results of temperature and reflectivity at different laser power.

From fig 3, When the laser irradiated on the foil, the absorptivity drop down slightly first because of the laser clean effect, then rise up when temperature higher than about 300℃. The dependence on temperature of absorptivity is similar when temperature is below 500℃ and the heating rate plays a vital role after that. The absorptivity is not only the function of temperature, but also the temperature history.

3. MATHEMATICAL MODEL AND SIMULATION RESULTS

When the clean metal surface is irradiated by the laser beam, absorbed energy starts to heat the surface. As the temperature increases, oxides nucleate and grow, and so a greater part of the incident radiation impinges on the oxides rather than the clean metal surface. Absorption does not take place directly at the surface, but in a thin surface layer. Therefore, when the oxide layer is thin, the laser–material interaction can be assumed to occur in several stages. First, as the laser beam impinges on the oxide layer, a part of the beam is reflected by the oxide layer. The fraction of the beam that is not reflected is either absorbed by the oxide layer, or transmitted to the metal surface beneath. The metal surface in turn absorbs a fraction of the transmitted radiation and reflects the rest. Radiation reflected from the metal surface is then either absorbed by the oxide layer or transmitted through it. Therefore, when the oxide film is thin, the total

absorptivity is dominated by the reflectivity of the metal surface, but as oxide film growth proceeds, the amount of energy absorbed by the work piece is dominated by the absorptivity of the oxide film and the heat transfer efficiency between the oxide film and the parent material. Assumptions of the absorptivity evolution under laser irradiation were listed below.

1) The oxide layer is a compact, perfectly adherent scale.
2) The oxide layer growth according to logarithmic rate, linear rate and parabolic rate law subsequently.
3) The optical constant of the oxide layer is uniform and stable when oxide layer growth.
4) Absorptivity can also be defined by A=1-R, where A is the absorptivity and R is the reflectivity.
5) The reflectivity according to the absorbing film on absorbing substrate model.
6) The foil is thin enough that lump parameter heat transfer method can be used.
7) The emissivity is equal to the absorptivity at the laser wavelength.

A mathematical model was build with the kinetic equation for the variation of oxide layer thickness x with temperature T reached on the irradiated surface of the target; the equation describing the dependence of absorptivity A on x and the equation of thermal conduction, connecting T and A. The equations were listed below.

$$\frac{dx}{dt}=\begin{cases} d_0\exp\left(-\frac{T_{d0}}{T}\right)\cdot\left[\exp\left(\frac{x_{th}}{x}\right)-\exp\left(-\frac{x_{th}}{x}\right)\right] & ,(x\le 20nm) \\ d_1\exp\left(-\frac{T_{d1}}{T}\right) & ,(20nm<x\le 50nm) \\ \frac{d_2}{x}\exp\left(-\frac{T_{d2}}{T}\right) & ,(x>50nm) \end{cases} \tag{1}$$

$$mc(T)\frac{dT}{dt}=A(x)P_{laser}-S\sigma\varepsilon\left(T^4-T_0^4\right)-S\eta(T-T_0) \tag{2}$$

where d_i (i=0,1,2) is the reaction constant that is independent of the absolute temperature T for logarithm rate law, linear rate law and parabolic rate law, T_{di} (i=0,1,2) is the activation temperature in Kelvin degree correspondingly. x_{th} is the characteristic thickness of the oxide layer against which the influence of the electric field is appreciated as either strong (with $x>x_{th}$) or weak (with $x<x_{th}$). P_{laser} is the laser power irradiation on the foil, the absorptivity of the layered metal-oxide film of thickness x, $A(x)$ is given by

$$A(x)=1-|r(x)|^2 \tag{3}$$

where $r(x)$ is the reflectivity of the layered metal-oxide film. For the case of normal incidence we have

$$r(x)=\frac{r_{12}+r_{23}\exp(j2\varphi)}{1+r_{12}r_{23}\exp(j2\varphi)} \tag{4}$$

where r_{12}, r_{13} and r_{23} are the amplitude coefficients of radiation reflection on air/oxide, air/metal, oxide/metal interface,

$$r_{12}=\frac{1-\sqrt{\varepsilon_c}}{1+\sqrt{\varepsilon_c}} \tag{5}$$

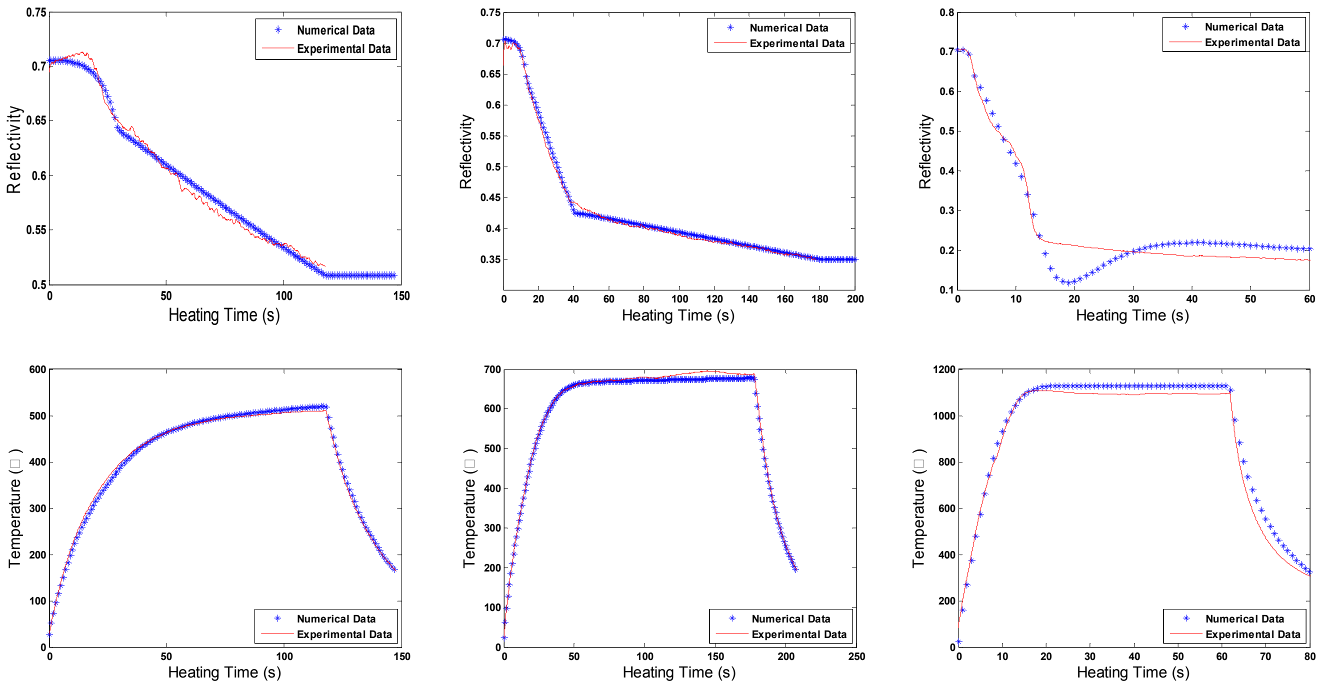
$$r_{23}=\frac{r_{12}-r_{13}}{r_{12}r_{13}-1} \tag{6}$$

$$r_{13}=\sqrt{1-A_M} \tag{7}$$

$$\varphi = \frac{2\pi}{\lambda} x \sqrt{\varepsilon_c} \tag{8}$$

where A_M is the absorptivity of the metal without the oxide film. λ is the laser wavelength, $\sqrt{\varepsilon_c} = n + ik$ is the dielectric permittivity of the oxide where n and k are the refractive index and the extinction coefficient for the oxide。

Numeral calculations were made for 30CrMnSi steel at wavelength 1.07μm, and the laser powers were same as the experiment. The other parameters needed were taken from handbook[5]. The dielectric permittivity was 3+5j for clean steel surface and 2+1j for oxide film. Based on equation (3) ~ (8), the reflectivity was about 0.69 for clean steel and 0.17 for very thick oxide film. The results were very close to the experimental data. The simulation results of temperature and reflectivity evolution under different laser power are shown in fig. 4.



(a) P=3.10W (b) P=4.93W (c) P=18.19W

Fig 4. Simulation results of reflectivity and temperature versus time at different laser power

From Fig4, it can be seen the simulation results are in agreement with the experimental data well when peak temperature is below Ac_1 phase transformation temperature. The structure of the foil would become austenitizing when it was heated up to temperatures above the Ac_1. Because the foil was thin enough, the temperature drop down so quickly that it convert from austenitic to martensite directly at about 280℃. The specific heat was small for austenitic structure thus the numerical results drop down a little slowly than the experimental data. No multi-beam interference was observed in experimental results. Overall, the numerical calculations of ordinary differential equations were in agreement with the experimental phenomena well.

4. CONCLUSION

In summary, in this paper we built an experimental apparatus to measure the reflectivity and temperature of the foil simultaneous. The experiment was executed in inert and oxidizing atmosphere. The experimental results showed that oxide film is the main reason of absorptivity changing. The absorptivity dropped down slightly first because of the laser cleaning effect and then rose up when temperature higher than about 300℃. Depending on the oxide film depth, the oxide film growth experienced 3 stages which corresponding to logarithmic rate law, linear rate law and parabolic rate law. The temperature dependence of absorptivity was insensitive to heating rate when temperature was below about

500℃. The heating rate played a vital role after that. A mathematical model was introduced to explain the phenomena observed in experiments. The numerical approach adopted for the self-consistent solution of the heat diffusion equation coupled with the oxidation kinetics equations showed to be very effective in the prediction of the laser absorptivity and temperature.

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